The Constellation X-ray Mission

Submitted on behalf of the Facility Science Team
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http://constellation.gsfc.nasa.gov

Mission Overview

The *Constellation* X-ray mission is an observatory class facility that will obtain detailed spectra for all classes of objects from nearby stars to distant AGN and clusters of galaxies. As illustrated in Figure 1, the *Constellation-X* design achieves its high throughput and reduces mission risk by dividing the collecting area across four separate spacecraft launched two at a time. The *Constellation-X* mission requires a large collecting area with emphasis on high spectral resolution ($R = E/\Delta E$ from 300 to 3000 for energies up to 10 keV) and a broad energy coverage (0.25 to 60 keV). By increasing the telescope aperture and utilizing efficient spectrometers, the mission will achieve a factor of 25 to 100 increase in sensitivity over current high resolution X-ray spectroscopy capabilities. The use of focusing optics across the 10 to 60 keV band will provide a similar factor of 100 increase in sensitivity for this band. Figure 2 shows the effective areas for the three *Constellation-X* instruments as a function of energy along with equivalent curves from the high spectral resolution instruments on-board *Chandra*, XMM-Newton and Astro-E2.

The *Constellation-X* mission will address many key science topics. These include measuring the effects of strong gravity close to the event horizon of super-massive black holes, determining the evolution of AGN and their central black holes with redshift, observing the formation and evolution of clusters of galaxies, and constraining the Baryon content of the Universe. Observations of stellar coronae, supernova remnants, and the interstellar medium will generate a wealth of information on chemical enrichment processes as well as detailed measures of plasma temperatures, pressures, and densities over a range of astrophysical settings.

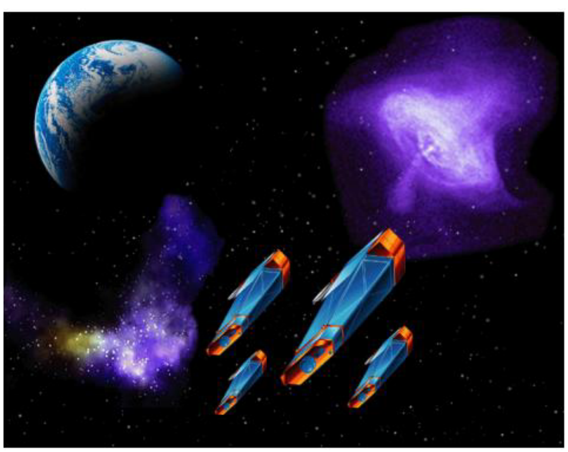

Figure 1: Four *Constellation-X* spacecraft.

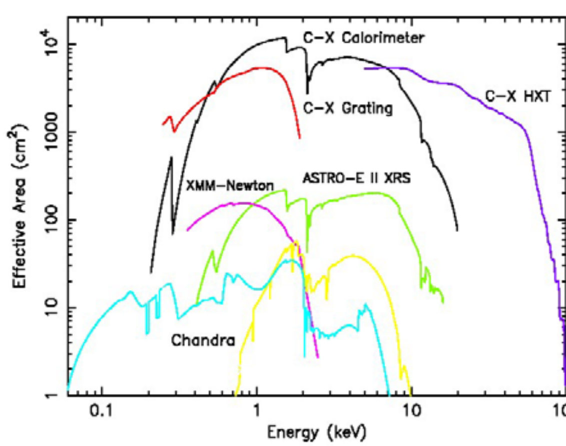

Figure 2: Comparison of *Constellation-X* effective area vs. energy to other missions.

Principal Science Goals

The 0.25–10 keV X-ray band contains the K-shell lines for all of the abundant metals (carbon through zinc), as well as many of the L-shell lines. The detailed X-ray line spectra are rich in plasma diagnostics, which also provide unambiguous constraints on physical conditions in the sources. A spectral resolution of R >300 is driven by the requirement to separate the He-like density sensitive triplet from ions such as O, Si, and S. In the region near the iron K complex a resolving power exceeding ~2000 is necessary to distinguish the lithium-like satellite lines from the overlapping helium-like transitions. Resolutions of 300–3000 provide absolute velocity measurements of 10–100 km/s, typical for many astrophysical systems. At present the high resolution spectrometers on *Chandra* and XMM-Newton can only reach the very brightest handful of sources. *Constellation-X* will finally make high resolution spectroscopy of faint X-ray source populations routine, and bring the power of spectroscopy to bear on a wide range of astrophysical problems.

X-ray spectroscopy of the iron Kα fluorescence line that is produced when X-rays illuminate dense, accreting material is a powerful probe of the dynamics and space-time geometry within a few gravitational radii of accreting supermassive black holes. *Constellation-X* will permit us to study these spectral features with extremely high sensitivity and, in particular, examine the detailed time variability of the relativistically broadened iron lines. Figure 3 shows two simulated *Constellation-X* snapshots of a relatively bright Seyfert I galaxy, with a flare occurring above the accretion disk. The figure illustrates the evolution of the wavefront and its effects on the Fe lines. Line variability signatures can be understood within the framework of General Relativity (GR), and can be used to infer the fundamental parameters of the black hole (mass and spin). With sufficiently exquisite data, such as to be produced by *Constellation-X*, one can conceive of line variability that cannot be understood within the context of GR. In such a case, one would have to consider possible modifications to Einstein's theory, or invoke the presence of extra fields in the vicinity of the event horizon which alter the particle and/or photon dynamics.

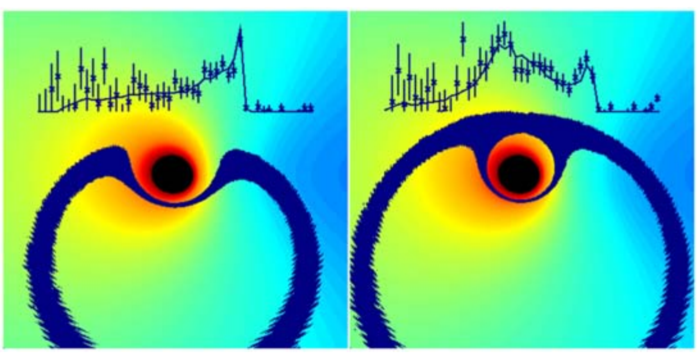

Figure 3: *Constellation-X* simulations of the variability of the Fe Kα line profile in an AGN during a flare.

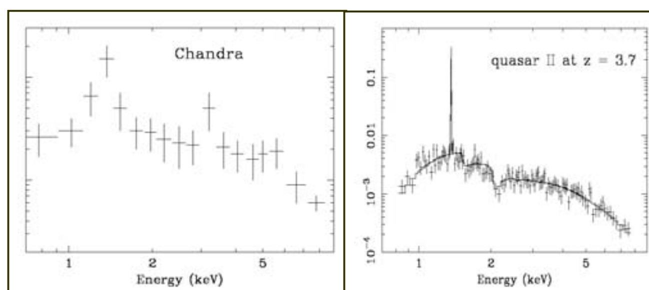

Figure 4: a) Chandra spectrum of a z=3.9 quasar. b) *Constellation-X* simulation of the same quasar showing the improved data quality.

The Hard X-ray Telescope on *Constellation-X* is essential for determining the underlying continuum in these sources enabling one to measure the properties of the broad lines to high accuracy. The Hard X-ray Telescope is also a key tool for observing highly obscured AGNs, which may be a significant contributor to the accretion luminosity of the Universe (if not the overall luminosity). Both *Constellation-X* telescopes are needed to study spectra of AGNs at redshifts > 1, which may hold important clues for the formation of galaxies and the overall evolution of the Universe. For some of the more distant, optically faint quasars discovered by *Chandra*, X-ray spectroscopy with *Constellation-X* may be the best (or only) way to determine their redshift and basic properties. Figure 4 shows the X-ray spectrum of a Type 2 quasar at z=3.9 detected in a 1 Msec *Chandra* exposure, along with a 100ks simulated *Constellation-X* spectrum. *Constellation-X* easily detects the Fe-line suggested at the 2-σ level in the *Chandra* data.

Constellation-X will determine with high precision the distribution of dark matter within elliptical galaxies and clusters of galaxies out to z~2. Figure 5 shows a 50ks simulated *Constellation-X* observation of a cluster with a temperature of 4 keV at a redshift of 0.8. A type II supernova abundance distribution was assumed. The abundance of Si, S and Fe are determined to 10% accuracy and Ne and Mg to 20%. At higher redshifts *Constellation-X* will obtain integral spectra of clusters and groups of galaxies, which will provide bounds on the dark matter and baryonic distribution. By determining how the relation of dark matter and baryons changes with redshift, *Constellation-X* will place constraints on the nature of the dark matter. Observations of nearby clusters by *Constellation-X* will verify (or challenge) our fundamental assumptions that the gas is in hydrostatic equilibrium and not dominated by turbulence or magnetic fields. The spectral resolution will measure the line widths and thus limit turbulence and mass motion, while the hard X-ray imager will place limits on magnetic fields by searching for non-thermal high-energy tails.

Numerous groups are planning large area sky surveys to detect clusters of galaxies via the Sunyaev Zel'dovich (SZ) effect. This technique can see clusters out to very high redshift (because the SZ signal is independent of z) and thus will be able to detect the first clusters in the Universe. The shape of the redshift distribution of SZ clusters provides a robust indicator of the mean density of the Universe, independent of the nature of the equation of state parameter. This provides a complementary constraint to the SN1a and CMB measurements of the dark energy as a function of redshift. The *Constellation-X* sensitivity and spectral resolution will be required to follow-up representative clusters in the SZ samples to confirm their redshifts (from the Fe K-line) and determine their masses (from the gas temperature and density). Note the redshift distribution of a mass-limited sample, which the X-ray data provide, is a much more powerful probe of the dark energy than the SZ detections (source counts) themselves.

The observed Baryons in the local universe fall far short of those predicted by standard big bang nucleosynthesis. Numerical simulations predict that most of these missing Baryons are in a hot intergalactic medium (IGM). This IGM should be detectable through X-ray absorption lines imprinted by highly ionized metals on the spectrum of background quasars. As shown in Figure 6, very faint (EW ~0.1 eV) absorption lines can be detected by *Constellation-X.*

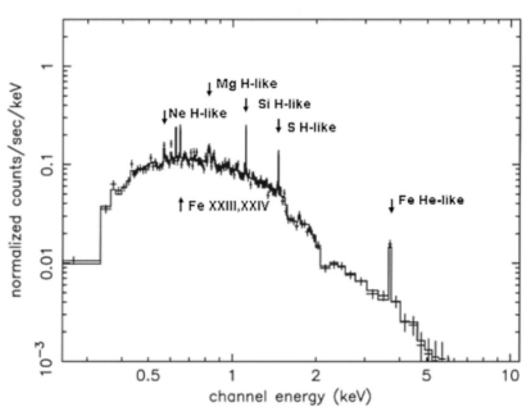

Figure 5: 50 ks *Constellation-X* simulation of a cluster at z=0.8 and kT=4 keV.

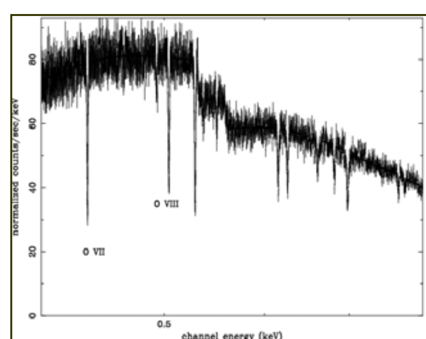

Figure 6: *Constellation-X* simulation of a bright, background quasar. X-ray absorption lines imprinted by highly ionized metals are easily detected.

Mission Design, Technology Development and Overall Status

The *Constellation* X-ray mission has been in formulation since 1996 with a focussed technology development program underway since then. A solicitation in 1998 selected teams to work on the critical technologies for the mission, including microcalorimeter arrays, Grating/CCDs, and Hard X-ray Optics/Detectors. A total seven proposals were selected via peer review. Three Integrated Product Teams (IPT) were formed with leaders appointed to coordinate these technology efforts. The optics for the main Spectroscopy X-ray Telescope (SXT) are being designed and evaluated by a joint GSFC-MSFC-SAO team, and most likely will be procured via a contract to industry.

The *Constellation-X* technology development effort is ramping up over the next three years (FY2002 through 2004) to support a new start in 2007, with launches in 2010 and 2011. All of the *Constellation-X* technologies are an evolution of existing, flight proven instruments and telescopes. Additional technology funding in FY04 and FY05 could enhance readiness at the end of this 3-year enhanced technology phase, with the possibility to advance the new start date to 2006 and launch dates by one year to 2009 and 2010.

The required large collecting area is achieved with a design utilizing several mirror modules each with its own spectrometer/detector system. The *Constellation-X* design recognizes that several smaller spacecraft and more modest launch vehicles (e.g. Delta-class) each carrying one "science unit" can cost less than one very large spacecraft and launcher (e.g. Titan-class). The program is then very robust in that risks are distributed over several launches and spacecraft with no single failure leading to loss of mission. The baseline mission is four satellites that are carried in pairs on either two Atlas V or Delta IV launchers. The satellites will be placed into orbits about the L2 point. This will facilitate high observing efficiency, provide an environment optimal for cyrogenic cooling, and simplify the spacecraft design. The interval between the two launches will be of order 1 year. The mission lifetime with all four satellites on orbit will be >5 years. There will be minimal consumables (primarily propulsion) and once on orbit the mission lifetime can potentially last much longer. A cooperative agreement notice (CAN) was issued with industry in 1998 and Ball Aerospace and TRW worked with the project at Goddard Space Flight Center on system level studies of possible mission implementations. Lessons learned from these industry studies have been incorporated into the current baseline missions design. It is important to recognize that the mission design is flexible and can be adapted to various launchers both current and planned.

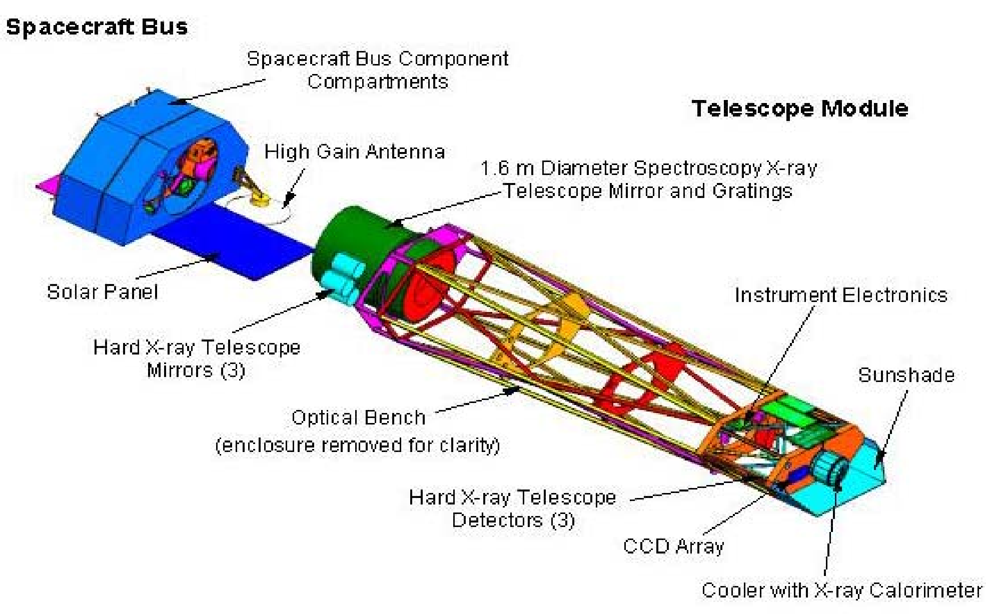

Figure 7: Drawing of the *Constellation-X* spacecraft layout.

The overall layout of 1 of the 4 *Constellation-X* spacecraft is illustrated in Figure 7, where the major elements are labeled. Each spacecraft is designed to have a separate spacecraft bus and an instrument module containing the SXT and HXT optics, optical bench and detector assemblies. This will allow for a standard off the shelf spacecraft bus and parallel production line development.

The first technology area under development emphasizes lightweight, high throughput X-ray optics for the SXT (0.2–10keV) and HXT (6–60 keV) to meet mission mass requirements. The segmented optic approach continues to be the most promising, with SXT mass and imaging performance at the component level approaching the mission requirements (15") and allowing for extension towards the angular resolution goal (5"). Figure 8(a) is a picture of two segmented sections being aligned, while Figure 8(b) shows the precision combs being used for the alignment. The angular resolution of the optics directly affects the data analysis and interpretation by avoiding source confusion, while allowing lower flux sources to be observed. Improved resolution of the SXT also translates into improved spectral resolution with the reflection grating, directly aiding in the study of weak emission and absorption lines. Increasing the spatial resolution of the HXT optics also dramatically increases the science return by reducing the background noise contributions. Increased throughput in the HXT is being pursued by development of multilayer coatings to enhance the hard X-ray reflectivity of the optics. Over the next 3 years, the project will develop prototype mirror segments for both the SXT and the HXT to demonstrate the required performance at the system level.

Figure 8a (below) Aligning two segmented mirror sections. Figure 8b (right) alignment combs.

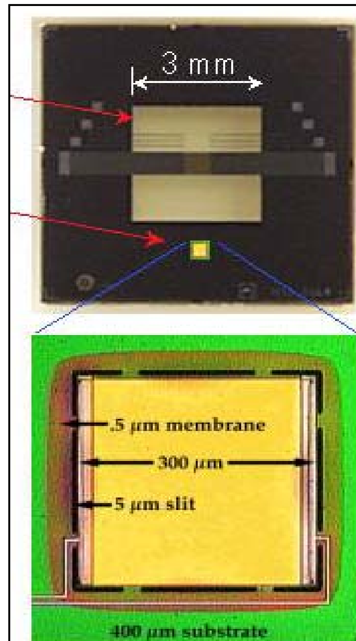

Figure 9: TES thermometer with silicon nitride perimeter.

The SXT reflection gratings also face the challenge of developing a lightweight design and an automated high yield process. Anisotropic interference lithography on silicon wafers, followed by replication on to lightweighted substrates, is being pursued to produce the gratings. A separate effort is underway to generate a high density (> 5000 l/mm), high efficiency, radial groove configuration that will allow an off-plane mount with the potential increase in spectral resolution by more than a factor of 4 over traditional in-plane gratings, while simultaneously reducing costs and mission risk by requiring fewer gratings.

The mission detector suite is another high priority area of technology development: microcalorimeter spectrometers with large arrays, high count rate consistent with the mission's effective area, and 2 eV resolution; low power and radiation tolerant resistive-gate (RG) CCDs; and hard X-ray imaging detectors. All of these technologies are based on enhancements in existing, flight proven detectors. Improving the energy resolution of the detectors simplifies data analysis and interpretation by removing ambiguities arising from line blending. Two parallel microcalorimeter efforts are being pursued to reduce risk and cost while ensuring performance: transition-edge sensors and NTD germanium. Both technologies are now approaching 2–4 eV resolution and count rate capability within a factor of a few of mission requirements; Moreover, the larger arrays required for *Constellation-X* are now in development. Figure 9 shows a TES thermometer, approximately the size needed for *Constellation-X*, with the silicon nitride perimeter, which provides good thermal isolation. The first lot of RG-CCDs has been fabricated to demonstrate the concept, but additional lots will be needed to demonstrate performance at the level needed for flight. Low noise ASICs for the HXT have been demonstrated along with detector performance at a lower energy threshold of ~ 2 keV, which should assure HXT performance to 6 keV or lower, providing better cross-calibration with the SXT and additional overall collecting area for *Constellation-X* in the 2–10 keV band.

Constellation-X Science as Priorities Identified in NAS Reports

Constellation-X addresses a number of very high priority science questions and is strongly supported by a number of National Academy of Sciences (NAS) reports. The NAS Astronomy and Survey Committee (2001) accords *Constellation-X* the second highest ranking (after NGST) among major space-based initiatives for the next decade. Their report - Astronomy and Astrophysics in the New Millennium - describes Constellation-X as *"The premier instrument to probe the formation and evolution of black holes - both stellar black holes in our galaxy and supermassive black holes in the nuclei of other galaxies. Constellation-X will also measure the physical conditions in the first clusters of galaxies, study quasars at high redshift, contribute to nuclear physics by measuring the radii of neutron stars, and trace the formation of the chemical elements… Constellation-X has been under active study for more than 5 years, and the technology issues are well in hand for a start in the middle of the decade."*

The NAS Physics Survey Overview Committee (2001) does not endorse specific missions by name; however, it does identify several high-priority "grand challenges", including "Exploring the Universe". In that context, the report states that *"New instruments through which stars, galaxies, dark matter, and the Big Bang can be studied in unprecedented detail will revolutionize our understanding of the Universe, its origin, and its destiny…New measurements will … help determine the nature of dark matter and dark energy… and the predictions of Einstein's theory for the structure of black holes may be checked against data for the first time. Questions such as the origin of the chemical elements and the nature of extremely energetic cosmic accelerators will be understood more deeply."* Here, we note that *Constellation-X* directly addresses many aspects of this grand challenge, as well as the questions about dark matter, dark energy, black holes and general relativity, origin of chemical elements, and energetic cosmic accelerators, which are among the key (11) questions identified by the NAS Committee on the Physics of the Universe. The CPU recommendations are expected to be public in March/April 2002.

The NAS Committee on Gravitational Physics (1999) also recommends astronomical observations, including X-rays, to study the environment near black holes as well as precision measurements using available technology, astronomical capabilities, and space opportunities to improve experimental testing of general relativity. These objectives are well-matched to the *Constellation-X* capabilities.

Connections with other NASA and non-NASA Missions

The NASA X-ray astronomy program has identified two long-term goals: 1) sufficient angular resolution (0.1 micro arc sec) to image the event horizon of a black hole and 2) sufficient collecting area (50–150 sq m) and angular resolution (0.1–1.0 arc sec) to observe in detail the first galaxies and black holes at high redshift (5–20). To realize these goals, two challenging "vision missions" are being used to guide NASA's technology program.

The first mission is the Micro-Arc second X-ray Imaging Mission (MAXIM) which will image a black hole using X-ray interferometry. As a precursor to MAXIM, *Constellation-X* will use X-ray spectroscopy to probe close to the event horizon of black holes and map the overall AGN environment. This is an essential first step, possible with technology available today, necessary to prove the feasibility of mapping the X-ray emission coming from close to the event horizon of a black hole.

The second vision mission is *Generation-X* which will have *Chandra*-like angular resolution, but ~1000 times the collecting area, both necessary to observe the first galaxies at high redshift (~10). The development of the precision arc second light weight optics required for *Generation-X* is well beyond current capabilities, but the *Constellation-X* optics program will provide the next major step towards realizing this goal. *Constellation-X* also will study the evolution with redshift of million to billion solar mass black holes in active galaxies at redshifts of order 1–4 (and perhaps beyond), while providing much more detailed spectroscopy of nearby galaxies, out to redshift of ~0.5. These are the critical science pathfinders for *Generation-X*.

ESA and ISAS are planning a major mission, XEUS, for the ~2016 timeframe. A prime objective of this mission is to observe the first black holes in the high redshift universe, similar to those of the NASA *Generation-X* vision mission. The current implementation plan for XEUS utilizes the International Space Station to assemble a 10m diameter X-ray optic. The final collecting area is 30 sq m with an angular resolution of 2–5 arc sec. The science goals and capabilities of XEUS and *Generation-X* are similar, and it seems possible that the two missions might merge at some point in the future, although at present the implementation approaches are very far apart.

Prior to *Constellation-X*, the approved mid-sized Japanese-US mission Astro-E2 will fly (~2005) the first X-ray micro-calorimeter array, the core detector technology for *Constellation-X*. The Japanese are considering a similar mid-sized class mission called NeXT for the 2010 timeframe. The details of this mission are still being defined, but it appears to emphasis hard X-ray imaging and is very synergistic with the *Constellation-X* HXT technology development program.

Addressing National Priorities

The Office of Science and Technology Policy (OSTP) identifies US SR&T priorities as science education, sustaining America's world-leading science and technology enterprise, national security, environmental quality, economic growth, and human health. *Constellation-X* contributes in several of these areas.

There is widespread public interest in studies of such exotica as dark matter, dark energy, and especially black holes. *Constellation-X* has already been reviewed and endorsed as a very high priority science mission by several National Academy committees. The NRC Physics Survey Overview Committee identifies the need to deepen the link between space-borne astronomy and fundamental physics which *Constellation-X* will accomplish through science objectives described above.

The technology developed for *Constellation-X* will support national security, environmental quality, economic growth and human health in a number of ways. Just as we probe cosmic X-ray emitters, so too can we analyze the elemental, chemical and structural composition of electronic, biological, geological and particulate materials on earth. Improved X-ray detection systems can be applied to medical and dental imaging, nuclear medicine, dosimeters, semiconductor defect detection, industrial radiography, nondestructive testing, heavy metals analysis, cargo inspection, nuclear safeguards and surveillance, treaty verification and environmental monitoring.

For the semiconductor industry, the microcalorimeter combines the broad-band energy response and high efficiency of conventional non-energy-dispersive detectors with the energy resolving power of the crystal spectrometer. Consequently, the microcalorimeter has the potential to advance the state-of-the-art for elemental and chemical analysis. When coupled to a scanning electron microscope through point-to-point X-ray concentrators based upon X-ray optics, it will engender the evolution of a new generation of microanalysis tools with greatly improved spatial resolution, increased sensitivity, and the ability to unambiguously identify X-ray signatures from a mixture of light and heavy elements. As lateral and vertical dimensions shrink, current surface diagnostic tools will no longer have resolution sufficient to identify defects. With an energy resolution of ~2 eV over the energy range of 0.2 keV to 20 keV, the microcalorimeter will satisfy the new demands of the microanalyst by combining the best features of dispersive and non-dispersive spectrometers.

From the medical perspective, high detected quantum efficiency (DQE), a measure of the combined effects of low noise and high contrast, provides the requisite foundation for advanced applications. Higher DQE means detectability even for low contrast objects, achievable at low dosages. Microcalorimeters and hybrid solid state semiconductor detectors with CdZnTe, CdTe but also GaAs and Si as the active medium show enormous potential for applications requiring high DQE and high spatial resolution. The diagnosis of cancer and blood vessel disease of the heart, brain, and limbs requires a specific morphology diagnosis such as micro-vessel angiography (imaging of blood vessels after the injection of an iodine compound into an artery to detect stenosis or other pathologies). By including such characteristics as fast acquisition (photon counting) and low noise into detector design from the start, one has a foundation for access to a large range of future advanced medical applications - including tomosynthesis, digital-subtraction angiography, and dual- and multi-energy imaging. Tomosynthesis generates images at several planes of arbitrary depth in a single sweep, thereby acquiring volumetric information, critical for more reliable mammography, for example.

Partnerships

This mission will be a general use facility, that is expected to engage a significant part of the astronomy and physics communities. The *Constellation-X* Facility Science Team (FST) is involved in overseeing the mission during its formulation phase. The membership is comprised of ~50 scientists from 30 different institutions and 5 different countries. In addition, another 20 scientists serve on the various science panels working with the FST. At present, the FST includes US scientists with support from NASA, NSF, DOE, NIST, and Smithsonian. There is also extensive participation from the UK, Denmark, Italy, and Japan along with dialog and science contributions from Germany, Netherlands, and France. Our approach encourages open exchange of ideas and discussion of technical progress without formally obligating NASA or the *Constellation-X* mission to any specific teaming arrangements or financial commitments at this point in time. We have stated an openness to multi-agency participation including foreign contributions to the mission, with decisions to be driven by performance demonstrated during the technology studies and by the open competition through the NRA for the science instruments.